Precision Higgs Masses with FeynHiggs 2.2

Thomas Hahn

Max-Planck-Institut für Physik
München

Motivation

Arguably the most important task of the LHC is to

- find a Higgs boson and, if it exists,
- measure its properties to distinguish different models.

Necessary on the theory side: precise predictions of

- masses, couplings, branching ratios, . . .

in a variety of models

- SM,
- real MSSM,
- complex MSSM,
- non-minimal flavour-violating MSSM,
- NMSSM . . .

The MSSM Higgs Sector

$$H_1 = \begin{pmatrix} v_1 + \frac{1}{\sqrt{2}}(\phi_1 + \mathrm{i}\chi_1) \\ \phi_1^- \end{pmatrix}, \qquad H_2 = \mathrm{e}^{\mathrm{i}\xi} \begin{pmatrix} \phi_2^+ \\ v_2 + \frac{1}{\sqrt{2}}(\phi_2 + \mathrm{i}\chi_2) \end{pmatrix}$$

Higgs Potential:

$$V = M_1^2 H_1 \bar{H}_1 + M_2^2 H_2 \bar{H}_2 - M_{12}^2 (\varepsilon_{\alpha\dot{\beta}} H_1^\alpha H_2^{\dot{\beta}} + \text{h.c.}) + \frac{g_1^2 + g_2^2}{8} (H_1 \bar{H}_1 - H_2 \bar{H}_2)^2 + \frac{g_2^2}{2} |H_1 \bar{H}_2|^2$$

- **Five physical states,** h^0, H^0, A^0, $H^\pm$ **(no ~~CP~~ at tree level).**
- **Input parameters:** $\tan\beta = v_1/v_2$, M_{A^0} **or** $M_{H^\pm}$.
- **Unlike SM, MSSM predicts** M_{h^0} **(cf. Gauge Couplings).**
- $M_{h^0} < M_Z$ **at tree level, excluded by LEP searches.**

Radiative Corrections

Significant quantitative and qualitative changes:

- M_{h^0} **receives large radiative corrections, e.g. the dominant one-loop corrections** $\sim G_F\, m_t^4 \log(M_{\tilde{t}_1} M_{\tilde{t}_2}/m_t^2)$.
- **The MSSM Higgs sector is connected to all others (in particular the scalar top sector) by loop corrections.**
- **~~CP~~ parameters lead to self-energies** $\hat{\Sigma}_{hA}, \hat{\Sigma}_{HA} \neq 0$ **and induce mixing between** h^0, H^0 **and** A^0:

$$\begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix} = \begin{pmatrix} U_{11} & U_{12} & U_{13} \\ U_{21} & U_{22} & U_{23} \\ U_{31} & U_{32} & U_{33} \end{pmatrix} \begin{pmatrix} h^0 \\ H^0 \\ A^0 \end{pmatrix}$$

Real MSSM (rMSSM)

- "Unconstrained (real) MSSM" has
  M_{A^0}, $\tan\beta$, 5 parameters in $\tilde{t}$-$\tilde{b}$ sector, μ, $m_{\tilde{g}}$, M_2.

- $M_{h^0} \lesssim 135$ GeV for $m_t = 175$ GeV.

  Heinemeyer, Hollik, Weiglein 1999

  Degrassi, Heinemeyer, Hollik, Slavich, Weiglein 2002

- Complete one-loop result + all presumably dominant two-loop corrections known.

- Remaining uncertainties:
  From unknown higher-order corrections: $\Delta M_{h^0} \approx 3$ GeV.
  From input-parameter uncertainties: $\Delta M_{h^0} \approx 4$ GeV for $\Delta m_t \approx 4$ GeV.

  Degrassi, Heinemeyer, Hollik, Slavich, Weiglein 2002

  Frank, Heinemeyer, Hollik, Weiglein 2002

  Allanach, Djouadi, Kneur, Porod, Slavich 2004

Complex MSSM (cMSSM)

- Complex parameters enter via loop corrections and can induce ~~CP~~ effects: μ, $M_{1,2}$, $m_{\tilde{g}}$, $A_{t,b,\tau}$.
- Known:
  - ▷ fermion/sfermion one-loop corrections,
  - ▷ some leading logs from remaining sectors,
  - ▷ leading two-loop corrections.

Pilaftsis 1999 – Pilaftsis, Wagner 1999 – Demir 1999 – Choi, Drees, Lee 2000 – Heinemeyer 2001
Carena, Ellis, Pilaftsis, Wagner 2000, 01 – Ibrahim, Nath 2001, 02 – Ham, Kim, Oh, Son, Yoo 2002

- Previously unknown:
  - ▷ remaining sectors at one loop ($5\ \mathrm{GeV}$ in rMSSM),
  - ▷ q^2 dependence at one loop ($\sim 2\ \mathrm{GeV}$ in rMSSM).
- **Much larger uncertainties than in the rMSSM.**

Corrections included in FeynHiggs 2.2

$$\begin{pmatrix} q^2 - M_h^2 + \hat{\Sigma}_{hh} & \hat{\Sigma}_{hH} & \hat{\Sigma}_{hA} \\ \hat{\Sigma}_{Hh} & q^2 - M_H^2 + \hat{\Sigma}_{HH} & \hat{\Sigma}_{HA} \\ \hat{\Sigma}_{Ah} & \hat{\Sigma}_{AH} & q^2 - M_A^2 + \hat{\Sigma}_{AA} \end{pmatrix}$$

- **Most up-to-date leading $\mathcal{O}(\alpha_s\alpha_t, \alpha_t^2)$ + subleading $\mathcal{O}(\alpha_s\alpha_b, \alpha_t\alpha_b, \alpha_b^2)$ two-loop corrections in the rMSSM (complex effects only partially included in two-loop part).**

  Degrassi, Slavich, Zwirner 2001 – Brignole, Degrassi, Slavich, Zwirner 2001, 02
  Dedes, Degrassi, Slavich 2003

- **Full one-loop evaluation (all phases included).**
- **Complete q^2 dependence.**
- **Full one-loop corrections for the charged Higgs sector.**

  Frank, Heinemeyer, Hollik, Weiglein 2002

Additional Features

- **New renormalization** ($\overline{\text{MS}}$/OS) for one-loop result.

  Frank, Heinemeyer, Hollik, Weiglein 2002

- "Δm_b" **corrections** = leading $\mathcal{O}(\alpha_s \alpha_b)$ terms for Higgs masses, couplings, etc.

  Carena, Garcia, Nierste, Wagner 2000

- **Non-minimal flavour-violating effects** (e.g. $\tilde{c}$–$\tilde{t}$ mixing).

  Heinemeyer, Hollik, Merz, Peñaranda 2004

- $\Delta\rho$ **at** $\mathcal{O}(\alpha, \alpha\alpha_s)$ as an additional constraint.
  $\Delta\rho \gtrsim 2 \times 10^{-3}$ indicates exp. disfavoured $\tilde{t}/\tilde{b}$ masses.

- $(g_\mu - 2)_{\text{SUSY}}$ as an additional constraint.
  Full one-, leading/subleading two-loop SUSY corrections.

  Heinemeyer, Stöckinger, Weiglein 2003

Output of FeynHiggs 2.2

- `FHHiggsCorr`: **All Higgs-boson masses and mixings:** M_{h_1}, M_{h_2}, M_{h_3}, $M_{H^\pm}$, α_{eff}, U_{ij}, $\ldots$
- `FHCouplings`:
  - ▷ **Couplings and Branching Ratios for the channels**

    $h_{1,2,3} \to f\bar f, \gamma\gamma, ZZ^*, WW^*, gg$ $\quad$ $H^\pm \to f\bar f'$

    $h_i Z^*, h_i h_j, H^+H^-$ $\quad$ $h_i W^{\pm *}$

    $\tilde f_i \tilde f_j$ $\quad$ $\tilde f_i \tilde f'_j$

    $\tilde\chi^\pm_i \tilde\chi^\pm_j, \tilde\chi^0_i \tilde\chi^0_j$ $\quad$ $\tilde\chi^0_i \tilde\chi^\pm_j$
  - ▷ **Branching Ratios of an SM Higgs with mass** M_{h_i}**:**

    $h^{\text{SM}}_{1,2,3} \to f\bar f, \gamma\gamma, ZZ^*, WW^*, gg$
- `FHConstraints`: **Additional constraints** $\Delta\rho$, $(g_\mu - 2)_{\text{SUSY}}$

Download and Build

- Get FeynHiggs-2.2beta.tar.gz from www.feynhiggs.de.
- Unpack and configure:

```
tar xvfz FeynHiggs-2.2beta.tar.gz
cd FeynHiggs-2.2beta
./configure
```

- Type make to build the Fortran/C++ part only.
  Type make all to build also the Mathematica part.
  Takes about 2 min to build on a Pentium IV.
- Type make install to install the package.
- Type make distclean to remove unnecessary files.

Note: no prerequisites (e.g. LoopTools) required as in previous versions.

Usage

Three operation modes:

- **Library Mode:** Invocation from Fortran or C++ program, linked against the `libFH.a` library.
- **Command-line Mode:** Standalone executable `FeynHiggs` reads parameter file in FeynHiggs or SLHA format and writes out the results.
- **Mathematica Mode:** MathLink executable `MFeynHiggs` makes FeynHiggs routines accessible in Mathematica.

All programs and subroutines are documented in man pages.

Library Mode

Subroutines contained in FeynHiggs 2.2:

- `FHSetFlags` - set the flags of the calculation,
- `FHSetPara` - set the MSSM input parameters directly, *or:*
  `FHSetSLHA` - extract the input parameters from an SLHA data structure,
- `FHGetPara` - retrieve (some of) the derived parameters (e.g. chargino masses),
- `FHHiggsCorr` - compute the Higgs masses and mixings,
- `FHCouplings` - compute the Higgs couplings and BRs,
- `FHConstraints` - evaluate $\Delta\rho$ and $(g_\mu - 2)$ constraints.

C++ users need to include `CFeynHiggs.h` for prototypes.

Couplings

Internal software engineering straightened out, e.g. access to couplings much simplified:

```
#include "FHCouplings.h"

      double precision couplings(ncouplings)
      double precision gammas(ngammas)
      double precision gammasms(ngammasms)
      ...

      call FHCouplings(couplings, gammas, gammasms)

      br_hZZ = BR(H0VV(1,3))
      lcpl_Htt = LCoupling(H0FF(2,3,3))
      rcpl_Htt = RCoupling(H0FF(2,3,3))
      ...
```

Command-line Mode

Input File

```
MT          178
MB          4.7
MW          80.450
MZ          91.1875
MSusy       975
MA0         200
Abs(M_2)    332
Abs(MUE)    980
TB          50
Abs(At)     -300
Abs(Ab)     1500
Abs(M_3)    975
```

Command

`FeynHiggs` *file flags*

Screen Output

```
------------------- HIGGS MASSES -------------------
| Mh0    =   116.022817
| MHH    =   199.943497
| MA0    =   200.000000
| MHp    =   216.973920
| SAeff  =  -0.02685112
| UHiggs =   0.99999346   -0.00361740    0.00000000 \
|            0.00361740    0.99999346    0.00000000 \
|            0.00000000    0.00000000    1.00000000

-------- DECAY WIDTHS AND BRANCHING RATIOS ---------
| GammaTot-h0    =  0.448747E-02
| GammaTot-HH    =   4.71901
| GammaTot-A0    =   4.73148
| GammaTot-Hp    =   1.24126
  ...
```

- **Loops over parameter values possible (parameter scans).**
- **Mask off details with** `FeynHiggs` *file flags* `| grep -v %`
- `table` **utility converts to machine-readable format, e.g.**
  `FeynHiggs` *file flags* `| table TB Mh0 > outfile`

SUSY Les Houches Accord Format

Input File

```
BLOCK MODSEL
    1    1
BLOCK MINPAR
    1    0.100000000E+03   # m0
    2    0.250000000E+03   # m12
    3    0.100000000E+02   # tanb
    4    0.100000000E+01   # Sign(mu)
    5   -0.100000000E+03   # A0
BLOCK SMINPUTS
    4    0.911870000E+02   # MZ
    5    0.425000000E+01   # mb(mb)
    6    0.175000000E+03   # t
  ...
```

Command

`FeynHiggs` *file flags* →

file`.fh`

```
BLOCK MASS
   25    1.12697840E+02    # Mh0
   35    4.00145460E+02    # MHH
   36    3.99769788E+02    # MA0
   37    4.08050556E+02    # MHp
  ...
BLOCK ALPHA
        -1.10658125E-01    # Alpha
  ...
```

- **{Uses / was developed into} the SLHA I/O Library.**
  Hahn 2004
- **SLHA can also be used in Library Mode with `FHSetSLHA`.**
- **FeynHiggs tries to read each file in SLHA format first. If that fails, fallback to native format.**

Mathematica Mode

Provides the FeynHiggs functions in Mathematica, e.g.

```
In[1]:= Install["MFeynHiggs"];

In[2]:= FHSetFlags[...];

In[3]:= FHSetPara[...];

In[4]:= FHHiggsCorr[]

Out[4]= {MHiggs -> {117.184, 194.268, 200., 212.67},
>         SAeff -> -0.37575,
>         UHiggs -> {{0.994782, 0.102021, 0},
>                    {-0.102021, 0.994782, 0},
>                    {0, 0, 1.}}}
```

- **Can use all Mathematica functions on the results (e.g. `ContourPlot`, `FindMinimum`).**
- **Convenient interactive mode for FeynHiggs 2.2.**

Spin-Off: SLHA I/O Library

- The SUSY Les Houches Accord defines a common interface for SUSY tools.

  Skands et al. 2003

- Reading/writing SLHA files not entirely straightforward.
- The SLHA I/O Library fills this gap:
  - ▷ Implemented as native Fortran-77 Library.
  - ▷ All data transferred in one double-precision array.
  - ▷ This array is indexed by preprocessor macros, e.g. `MinPar_TB` instead of `slhadata(20)`.
  - ▷ Main functions: `SLHARead`, `SLHAWrite`.

  Hahn 2004

- Freely available at http://www.feynarts.de/SLHA.

Summary

- FeynHiggs 2.2 provides Higgs-boson masses, couplings, branching ratios, etc. in the real or complex MSSM.
- Full one-loop evaluation including q^2 dependence.
- Latest leading and subleading two-loop corrections. Inclusion of complex phases at two loop in preparation.
- Easy to build. Three operating modes: Library Mode, Command-line Mode, Mathematica Mode.
- Command-line Mode reads files in native or SLHA format.
- Download from http://www.feynhiggs.de. Maintained by S. Heinemeyer and T. Hahn.
- Spin-off: SLHA I/O Library. Download from http://www.feynarts.de/SLHA.